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Evolutionary processes in clusters

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Abstract

Are the morphologies of galaxies imprinted during an early and rapid formation epoch or are they due to environmental processes that subsequently transform galaxies between morphological classes? Recent numerical simulations demonstrate that the cluster environment can change the morphology of galaxies, even at a couple of cluster virial radii. The gravitational and hydrodynamical mechanisms that could perform such transformations were proposed in the 1970's, before the key observational evidence for environmental dependencies - the morphology-density relation and the Butcher-Oemler effect.

1.1 Introduction

Galaxies are observed to have a wide range of morphologies and stellar configurations, classified as disk-like with subclasses depending on the degree of disk instability, gas fraction and central nucleation, or spheroidal configurations of varying shapes and concentrations. Amongst both of these broad sequences we have various combinations of irregularities, subclasses, sizes, luminosities and star formation histories. Observational studies of clusters and groups have played an important role in helping us to understand the origin of galactic morphologies. This is due to three main reasons: (i) evolutionary processes are accelerated in high density environments, (ii) some classes of galaxies are only found within larger virialised systems and (iii) clusters can be found easily at higher redshifts and therefore can be used to detect evolution directly.

The observational data are consistent with the idea that the visible baryons are concentrated at the center of much larger dark matter halos (Fischer etal 2000). Thus the interpretation of galaxy morphologies is closely linked to understanding dark matter clustering on different scales. The baryons are observed to have a scale length that is about 1/10th of that of the dark matter implying that dissipation must have played a key role in galaxy formation. On average, galactic mass halos have accumulated close to the universal baryon fraction implying that violent feedback that leads to mass ejection of baryons has played a less important role in determining galaxy morphology. If most of the baryons quietly dissipated with little merging between subhalos, then the first galaxies to form are expected to be disks due to conservation of angular momentum as the gas radiates energy, sinks within the dark matter halos and spins faster. Indeed, most of the galaxies in quiet environments

(outside of other virialised systems) are disks - nearly all other classes of galaxies are found orbiting inside deeper potentials as satellite galaxies (halos within halos).

Spheroidal stellar configurations span a factor of 10^7 in luminosity from central cluster cD's to the local group dwarf spheroidals - whereas the disks range from the giant LSB's to the tiny Local Group dIrr's. In general the spheroidals reach higher masses and luminosities. It is not obvious why this is the case - the gas cooling timescale limits the maximum size of cold baryonic systems but it is a puzzle why we do not observe $\sim$30kpc disks at the centre of clusters where the cooling times are short. Perhaps harassment or local feedback from a central AGN may be suppressing central disk formation in massive halos.

The fact that few spiral galaxies are found anywhere within the central regions ($\sim$Mpc) of rich clusters (Dressler 1980) could be explained in two ways: (i) cluster galaxies were never disks since they formed in a more merger prone environment as lenticulars (S0), spheroidals (E) or dwarf ellipticals (dE), or (ii) disks formed first and have subsequently been transformed into other morphological classes by virtue of the cluster environment that formed later. The Hubble Space Telescope allowed a direct observational test of the morphological change over the past few Gyrs within dense and proto-dense environments. High resolution images of the "Butcher-Oemler" (Butcher and Oemler 1978) clusters at $z \sim 0.5$ showed that the luminous spheroidal population was already in place at this epoch but that the majority of the other galaxies were indeed disks (Dressler etal 1997), and even the S0 population is difficient (Smail etal 1997).

Many of these distant Butcher-Oemler clusters are complex merging systems of groups that will eventually have similar masses and galaxy densities to the nearby rich clusters like Coma. Clusters at high redshift that already have the mass and virial state of a rich cluster may already look similar to Coma, for example MS1054 (van Dokkum etal 1998). These comparisons are complex due to projection effects and background subtraction, but also the interpretation is difficult since frequently one is comparing systems identified at different epochs that are in different states of virialisation.

1.2 The paradigms for disk and spheroid formation

In order for gas to concentrate and form stars at the centers of dark halos it must first be shock heated so that it can dissipate and cool to high densities. As it cools it must spin faster as it conserves is primordial angular momentum generated from tidal torques (Hoyle 1949). The natural end state of cooling gas within an isolated DM halo is a rotationally supported disk; thus one might postulate that disks are the initial building block from which the entire morphological sequence is constructed. Once the first disky objects have formed (or even whilst they are forming), a process of multiple mergers and the associated central gas inflows are expected to create the cD, E sequence that extends to the faintest ellipticals - the high surface brightness M32-like systems.

It should be remembered that this is primarily theoretical speculation - the details of this process are far from being worked out and considerable numerical resources are required to fully investigate these ideas. Firstly we need to understand how the gas is shock heated and cools to the central disk and how the angular momentum of the gas evolves during this process. Forming a bulgeless late type disk galaxy may be one of the most difficult challenges for the CDM model. Understanding the formation of spheroids has equally challenging problems. For example, why is there such a narrow spread in the luminosity of cD galaxies and why do they lie offset brightwards from the galaxy luminosity function? Why

are the smallest ellipticals rotating faster than the massive ellipticals? Why are there so few isolated field ellipticals that are the probable end state of the M_* groups, where M_* is the characteristic non-linear mass today? The kinematics, colours and ages of ellipticals are also challenges for this paradigm that have yet to be understood. On a more general note, it is still unclear how CDM type models that predict a steep mass spectrum of halos can produce a flat luminosity function, whilst at the same time matching the correlation between baryonic mass/luminosity and dynamical mass.

Independent of the model, we can pose the question whether it is theoretically possible to reproduce the entire sequence of galaxies starting from disky systems? Starting with Holmberg's (1948) N-body experiments with lights and photometers and later confirmed by Toomre's computer calculations (Toomre 1977), it has been shown that it is possible for galaxies to interact gravitationally and produce spectacular tidal features. Longer numerical calculations performed by Gerhard (1981) showed that the end states of mergers will violently relax into spheroidal configurations, but additional dissipation is required to produce the high phase space densities observed in ellipticals. As is usual with N-body simulations, the detailed comparisons can be quite complex and the more details one simulates the more discrepancies one finds between data and theory (Naab etal 1999). More realistically, most ellipticals probably formed from the rapid and multiple mergers of a variety of baryonic systems - not too unlike a clumpy monolithic collapse and distinguishing between the two standard hypotheses is difficult. However in this review I will concentrate on "non-merging" mechanisms that can drive evolution and transform galaxies between and across morphological classes in the environments of galactic, group and cluster halos.

1.3 Mechanisms for transformation

Early theoretical work predicted that clusters of galaxies are harsh environments for galaxies to inhabit. Hydrodynamical processes (Spitzer & Bade 1950, Gunn & Gott 1972, Cowie & Songalia 1977, Norman & Silk 1979, Nulsen 1980) were proposed as important mechanisms for stripping the interstellar medium from galaxies. The importance of gravitational encounters and tidal forces as a mechanism for forming central cD galaxies, creating diffuse light and for influencing morphological transformation was proposed by many authors in the 1980's (Gallagher & Ostriker 1972, Ostriker & Tremaine 1975, Richstone 1976, White 1976, Hausman & Ostriker 1977, Merritt 1983).

Many of these mechanisms are efficient only in massive galaxy clusters and they may be invoked to explain the morphology density and Butcher-Oemler effects (Solanes etal 1992, Kauffman 1995). However the role of evolution in lower density environments may play an important role. The evolution of bright/massive galaxies within groups and poor clusters with dispersions below 400 km/s should be dominated by dynamical friction and mergers. An important question remains - is galaxy evolution in clusters driven by pre-processing of galaxies in groups? Indeed, star formation appears to be truncated within galaxies that lie in lower density environments (Balogh etal 2000). However, it is clear that galaxies in virialised systems have different morphologies than the field. If environment is responsible for transition, then it should be possible to quantify observationally and theoretically where, when and how these transitions take place.

In his excellent book on clusters, Sarazin (1980) makes six points to argue that the morphologies of galaxies are set at the time of formation rather than by subsequent environmental processes. Many of these points are still open questions. For example, Dressler (1980)

claimed that the bulges of S0's are more luminous than those of the spirals – a frequently cited result that was disputed by Solanes etal (1989) who analysed the entire Dressler sample and took into account additional selection effects. Most of Sarazin's arguments were made with the idea that gas processes would be driving a morphological evolution – Sarazin makes the point that gas dynamics would not reproduce the thick disks of S0's, however it is a natural outcome of gravitational interactions.

Indeed, recent numerical work has demonstrated that gravitational and hydrodynamical processes could be responsible for many of the observed aspects of galaxy morphology and evolution in different environments (Byrd & Valtonen 1990, Valluri & Jog 1991, Valluri 1993, Summers etal 1995, Moore etal 1996, Dubinski 1998, Moore etal 1998, Abadi etal 1999, Dubinski etal 1999, Mihos 1999, Quilis etal 2000, Vollmer etal 2000, Balogh etal 2000, Mayer etal 2001, Vollmer etal 2002, Gnedin 2003a, 2003b). The following sections will discuss these studies in the context of understanding the wide variety of galactic morphologies.

1.4 A new paradigm for the formation of S0/dS0/dE/dSph/UCD galaxies

Once a disky object has formed then it may enter a denser environment, whether a galactic, group or cluster mass system. If the velocity dispersion of the deeper potential is more than ∼five times the velocity dispersion of the infalling galaxy then it is unlikely to merge with either the central object (by dynamical friction) or with another satellite. Only external processes will effect its evolution and we can speculate, with support from numerical simulations, that the entire sequence of remaining galaxies (S0, dS0, dE, dSph...) is created by the transformation of spiral or dIrr systems by impulsive and resonant gravitational interactions with some additional help from hydrodynamical processes.

Ram pressure stripping is effective at removing the entire gas supply from galaxies that pass through the cores of rich clusters (c.f. Figure 1.3). This will supress star-formation in cluster galaxies but will it be effective at large distances from the centres of clusters where the gas density is low? Gravitational interactions may be important over a larger region of the cluster since more dark matter is bound to galaxies further from the central cluster potential (thus the encounters are stronger) but the number of encounters between halos decreases. The orbits of galaxies in clusters are nearly isotropic, which results in most of the galaxies orbiting through the dense inner region of the cluster (Ghigna etal 1998). In fact 10% of orbits will take galaxies through the core and to beyond twice the cluster virial radii (∼6 Mpc for Coma). Therefore the environment near rich clusters may host galaxies that have suffered significant gravitational perturbations and have been partially stripped of gas (c.f. Figure 1.2) by virtue of orbiting through the cluster core.

The definition of an S0 is basically a featureless disky galaxy with little or no ISM, so the simplest way to create an S0 is to remove the ISM from a Sa/Sb disk (Solanes etal 1989, 1992). We have two possible methods for accomplishing this. Any galaxy passing through the core of a massive cluster will have its gas supply completely stripped by ram-pressure and viscous stripping on a timescale smaller than the core crossing time. The remaining dense molecular gas may recycle into the ISM and also be removed or consumed in a burst of star-formation due to the pressure increase as the galaxy reaches the cluster center. Alternatively, gravitational interactions with the cluster and its substructures will heat disks, raising the Toomre "Q" parameter, which naturally suppresses spiral structure and other instabilities in

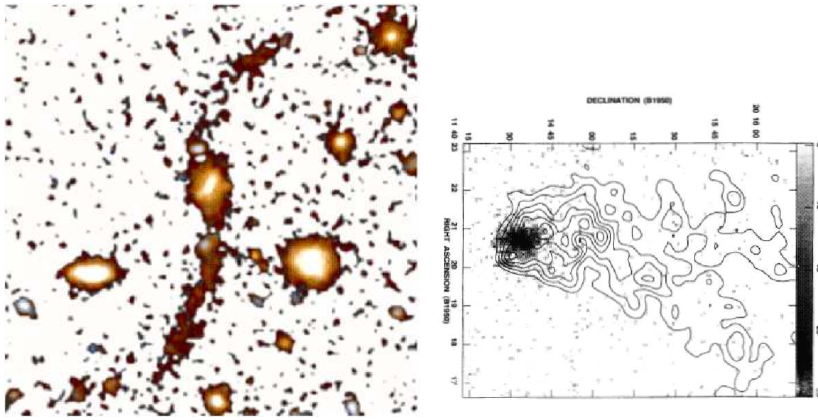

Fig. 1.1. The left image shows a symmetric stellar tidal tail from a disk galaxy that is orbiting in a galaxy cluster at z=0.5 (Courtesy of I. Smail and the MORPHS group). The right image shows the trailing radio emission from the hydrodynamical stripping of a cluster galaxy (courtesy of G. Gavazzi). Direct observational evidence for either gravitational or hydrodynamical effects are hard to find. In general, the tidal debris from harassed disks is too faint to observe, and ram-pressure stripping acts on such a short timescale that it is rare to catch a galaxy in the act of being stripped.

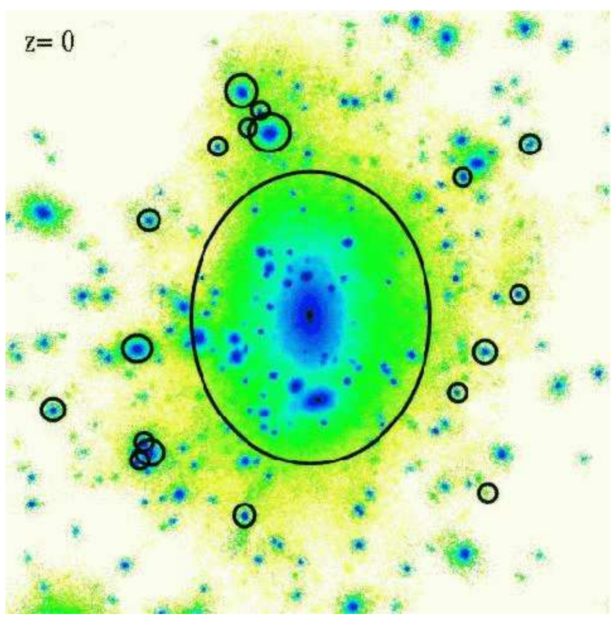

Fig. 1.2. The density of dark matter plotted to 3 virial radii for a high resolution simulation of a galaxy cluster. The large inner circle is the virial radius of the cluster. The smaller circles highlight halos that are currently outside the cluster but have orbited within $0.25r_{200}$. (This is the final frame of the mpeg movie showing the formation history of this cluster and can be downloaded from www.nbody.net.)

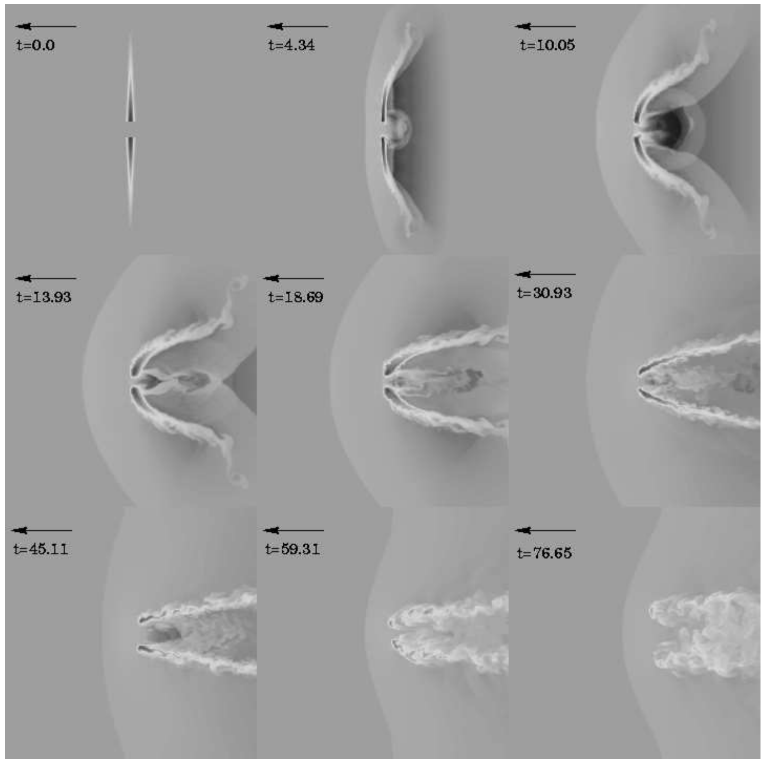

Fig. 1.3. A high resolution Eulerian simulation of gas stripping of a galaxy falling into a gas density representitave of the centre of the Coma cluster at 3000 km/s (Quilis etal 2000). The time unit is millions of years and each frame is 50 kpc on a side.

the disk, further suppressing star-formation as molecular cloud growth is halted (Moore etal 1998, Gnedin 2003a, Gnedin 2003b).

1.4.1 Cluster dwarf ellipticals (dE's) and transition galaxies (dS0's).

Dwarf ellipticals are the most numerous type of galaxy in clusters (Bingelli etal 1985). They are flattened exponential systems, sometimes with a bright compact nucleus. These systems are in various dynamical states ranging from pressure supported spheroids to rotationally flattened disky systems (Geha etal 2002). Numerical simulations of disks orbiting within cluster potentials have shown that a dramatic transformation to a diffuse spheroidal system is likely to occur (Moore eta 1996). The transformation sequence begins with a violent bar instability. Subsequent perturbations cause the bar to lose angular momentum and it eventually collapses into a spheroidal system through a buckling type instability. During the early stages of the transformation, which takes roughly a cluster orbital time, the morphology of the galaxy may appear as a rotationally supported dS0 system.

A fundamental prediction from gravitational heating mechanisms is that dE's should be embedded within very low surface brightness tidal streams of stellar debris, as demonstrated in Figure 1.4, and these streams should trace the orbital path of the progenitor galaxy. Since

the relaxation time is only short in the cluster cores these streams should survive relatively intact at the edge of clusters, but they should become well mixed near the cluster centres.

1.4.2 Intracluster diffuse light, overmerging and UCD's

The nature of the dark matter is critical to the survival of galaxies in clusters. If galaxies had constant density cores of just a few kpc (or cuspy potentials with very low concentrations) then they would all be easily disrupted by the cluster potential. This process is directly analogous with the overmerging problem that was responsible for the dissolution of subhalos in early N-body simulations (Moore etal 1996). On the other hand, if galactic halos are cuspy and concentrated they would all survive in clusters and we would not expect to observe a significant component of diffuse light.

The Ultra Compact Dwarfs recently found in the Fornax cluster are most likely the dense nuclei of nucleated dE galaxies that have been "overmerged" by gravitational interactions (Drinkwater etal 2000). These tracer cores show that the central concentrations of the progenitor galaxies must have been low enough such that they have been completely disrupted by the present day. Both the fraction of diffuse light stripped from galaxies and the abundance and locations of the UCD's could be used to constrain the structure of galaxies and the efficiency of gravitational interactions in different environments.

1.4.3 Local group dwarf spheroidals

The Local Group dwarf spheroidals are the extreme tip of the galaxy luminosity function, and as the shallowest potentials and faintest galaxies known they provide a strong test of our understanding of galaxy formation (Kormendy 1989). The Local Group morphology-density relation is similar to that of rich clusters in that the spheroidal galaxies with no diffuse gas are located close to the host galactic potentials of the Milky Way and M31. Again we can ask the question: do disks know not to form near the site of a massive potential or were they originally disks that have been transformed to spheroidals through interactions? Observationally this is unclear and a difficult question to answer since we can't observe Local Group progenitors at high redshifts.

However, a huge amount of detailed data exists for these faint Local Group galaxies (e.g. Grebel 2001), which must be reproduced by a successful model for their formation. Simulations of galaxy formation in a cosmological context that can resolve the faintest satellites are some years away, therefore only the most basic comparisons between theoretical models and data have been made to date. The dynamics of these systems indicate that their spheroidal shapes are due to random stellar motions and that rotational support is small. Many of these systems show evidence for continuous star-formation, or widely separated bursts, indicating that ram-pressure stripping by a hot Galactic halo component has not been completely efficient at removing their fuel. It also indicates that supernovae winds have not been effective at ejecting the bulk of the gas from these systems.

Galaxies are on average some 5 Gyrs older than galaxy clusters, which allows time for gravitational interactions to transform disks to dSph's in the potential of a more massive system (Mayer etal 2001). A high density Draco like dSph must have had a progenitor with a similar high dark matter density, such as the dIrr galaxy GR8. However, one should not compare GR8 directly with Draco since GR8 has evolved for 10 Gyr longer in the field than the system that accreted into the Galaxy to evolve into Draco. The morphological transformation predicted by the numerical simulations is similar to that for cluster galaxies,

but on a longer timescale since only the main galactic potential has been considered as the perturber. If the CDM model is in fact correct then the transformation for the dSph's may be more rapid due to encounters with dark matter substructure predicted to fill galactic halos.

1.5 Conclusions

Numerical simulations have shown that environmental processes are sufficient to reproduce some of the basic properties of a large fraction of the Hubble sequence (S0, dE, dS0, dSph, UCD) by gravitationally interactions acting on disks. Hydrodynamical processes can can also play a role in suppressing star-formation on a shorter timescale but only in regions of high gas density. Dramatic improvements to the modelling will come when algorithms have improved to the extent that we can form realistic disk systems from ab-initio initial conditions. This will allow the morphological evolution in groups and clusters to be studied in great detail and within a cosmological context, enabling quantitative observational comparisons and predictions to be made. Realistically this is probably 5–10 years away. For comparison with theory, observers need to quantify the Butcher-Oemler effect using mass selected samples of clusters at different epochs through a combination of lensing and high resolution spectro-photometric data. Probing down to dwarf galaxy luminosities and group mass scales will be of great interest to theorists working to constrain evolutionary scenarios and cosmological models.

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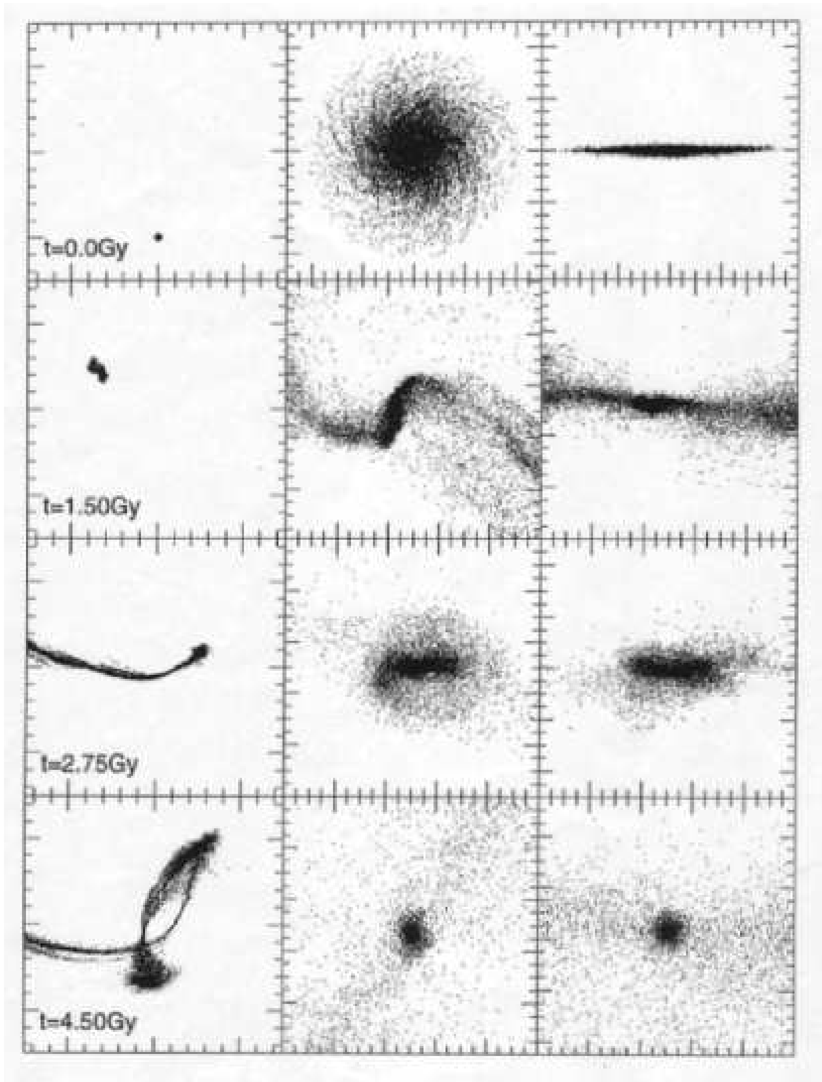

Fig. 1.4. Gravitational tides from a deeper potential are sufficient to drive an evolution from disks to dwarf spheroidals. Here I show the evolution of an Sc spiral galaxy on a 6:1 (apo:peri) orbit where the pericenter is $0.1r_{virial}$ and the ratio of circular velocities of the two systems are 5:1. This system could therefore be rescaled to represent a galaxy like the SMC orbiting within the Milky Way or an L_* LSB galaxy orbiting in a galaxy cluster. The left frame shows the entire orbit whilst the center and right frames are face and edge on views centred on the galaxy. The forced bar instability is so violent that the evolution is better described by a secondary violent relaxation of the stellar disk – most of the galaxy is stripped into symmetric debris streams leaving a small pressure supported spheroidal galaxy with an exponential light profile (courtesy of C. Calcaneo-Roldan).